Chapter 11
Deformation Monitoring

11-1. General

This chapter provides guidance for performing field measurements in support of the RLR technique of periodic structural monitoring. This method provides a direct measurement of displacement as a function of time, and has fewer problems of evaluation than most other types of instrumentations. The Robertson method is broken down into two parts: the initial setup of the control network, and the periodic measurement to determine movement. An EDM or total station and trilateration techniques are used for this type of deformation monitoring.

11-2. DME

All modern DME measure distance by timing, in an indirect fashion, how long it takes light to make a round trip to a reflector. By knowing the velocity of light, the distance may be calculated from 2d = vt, where d is the distance to the reflector, v is the velocity of light, and t is the time required for light to travel to the reflector and back. Light travels 1 foot in approximately a nanosecond. Therefore, other methods must be used to avoid the problems of timing a pulse to a small fraction of a nanosecond. In surveying a continuously operating source of light is used, and this light is modulated in a known way (i.e., the light is turned off and on in a regular fashion). The modulation wavelength λ_m is determined by the rate at which the light is modulated and by the velocity at which the light is traveling. A measurement is then made of the phase difference between the light proceeding toward the reflector and that returning. In an instrument built with a 20-m-modulation wavelength, the same result would be obtained every 10 m. For example, if an answer of 3.462 m resulted from a measurement (with a 20-m-modulation wavelength), the operator would not know if the complete answer would be 3.462, 13.462, 23.462, or 2,183.462 m. It would then be necessary to switch to a longer modulation wavelength. If the new wavelength were 10 times longer, the instrument would be able to determine the correct value of the figure in the tens place. To determine the figure in the hundreds place, the wavelength would again be increased ten times. This procedure would be repeated until the entire distance was resolved. Some instruments require five or six modulation frequencies to resolve ambiguities completely. By using the phase comparison method, instruments can be built that measure to better than one-thousandth of a modulation wavelength. Thus, certain instruments have resolutions finer than 0.001 m.

11-3. DME Error Sources

This section refers specifically to error sources, which is an inherent property of the instrument itself and is in addition to external factors, such as plumbing and measurements of refractive index. These systematic errors are usually written as (a) mm + (b) mm/km, where (a) and (b) are maximum values for a particular instrument.

a. Constant instrument error. The (a) portion of the error is a combination of several small errors, which are independent of the length of the line being measured. The more important of these are:

(1) Instrument resolution. Resolution is a property of the instrument that results from its original design. In the case of DME, it might be defined as the smallest change in distance to a target that causes a corresponding change in the reading obtained from the instrument. The resolution can be no finer than the scale or digital display can read. However, a display that can be read to a millimeter is no assurance that the resolution of the instrument is also a millimeter.

(2) Cyclic or delay line error. If the manner in which the light is modulated distorts the sinusoidal pattern of the outgoing beam or if the phase comparison technique of measuring the returning beam is less than perfect, a cyclic error will occur. The error is named cyclic because it repeats itself every modulation wavelength. If the effective modulation wavelength of a particular instrument is 10 m and the cyclic error for a measurement of 6 m is 4 mm, then the cyclic error at 16, 26, and 36 m would also be 4 mm. At the same time, the instrument might have zero cyclic error at 1, 11, and 21 m. A determination of cyclic error consists of making comparative measurements throughout a modulation wavelength.

(3) Instrument-reflector calibration. When a DME is received from the manufacturer, one or more reflectors are usually received at the same time, and these have been assigned a calibration constant by the manufacturer. This constant is to be added or subtracted from a distance reading in order to obtain a correct distance. In most cases, the constant is sufficiently accurate for routine work. However, for greater precision or for reflectors that are obtained from other sources, it is necessary to determine accurately the constant of each reflector. Figure 11-1 shows two reflectors, both of which are mounted

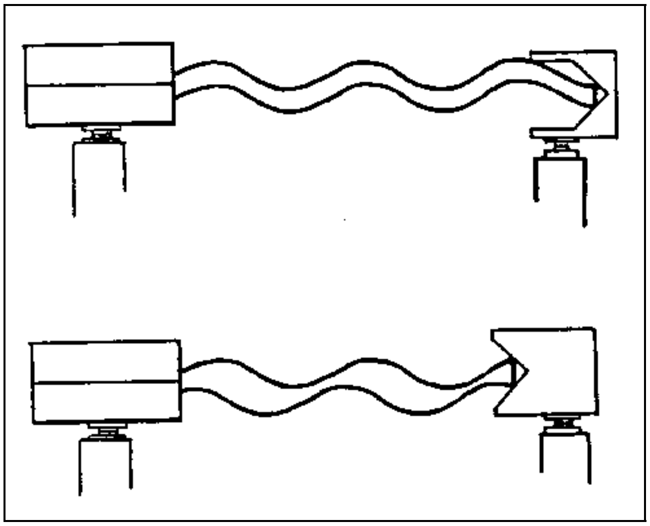

Figure 11-1. Reflector calibration

at the same distance from the measuring instrument. Because the reflectors are at different positions with their mounts, they give different readings for the same distance. The difference between the true distance and the reading obtained with a particular reflector is the instrument-reflector constant.

(4) Offset. The reflector calibration includes two sources of error. The first error is caused by the reflector not being optically above the point over which it is plumbed. The second error is caused by the DME electrical center, the point from which the instrument measures, not being over the point over which it is plumbed. However, both errors are corrected when the instrument-reflector combination is calibrated. On the other hand, if the electrical center of the instrument should shift as the electronics age, the instrument-reflector constant would no longer compensate for this shift, and an offset error would result. Even so, it is possible to measure the magnitude of the offset error. At weekly intervals, simply measure a short line (100 m) using the same reflector (the line should be outside so that the instrument will be subject to a variety of temperatures). If each measurement is made using the same procedures, the differences in length in excess of the resolution error are due to changes in the offset or electrical center of the DME. Temperature and pressure corrections must be made to these measurements. Offset changes of 5 mm may occur in some instruments.

(5) Pointing error. The modulation wave front issuing from a properly designed and operating instrument is at all points equidistant from the center of the instrument (Figure 11-2). It might be likened to the waves around a stone dropped into water. However, the wave front may be distorted in passing through the modulator, and then a portion of the wave may be ahead or behind the remainder. In Figure 11-2, the instrument sees both reflectors as equidistant because the phase of the modulated wave is the same for both. If the instrument is moved in azimuth slightly, the distance that is read would change. This type of error may be detected simply by multiple pointing at a reflector. If different pointings yield different results, it may be necessary to take several readings in the field, swinging off the target and then back until two or three sets of readings agree well. Practice in the field may help eliminate this problem as an experienced operator tends to point and adjust an instrument in the same way for each measurement.

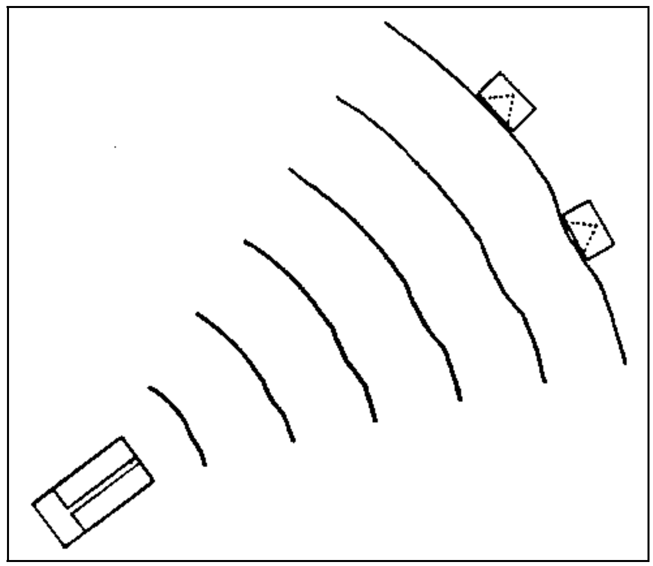

Figure 11-2. Pointing error

(6) Total error. The previous sections have treated individually the various types of errors in the (a) portion that may be present in DME. However, the total error (a) is all that is desired.

b. Measurement dependent errors. The second (b) portion of the error is due to the short- and long-term variations in the frequency standard used to control the modulation frequency. This is usually a quartz crystal, which may or may not be mounted with a small oven for temperature control. The only proper method of checking this frequency is by using a properly calibrated electronic counter. Some manufacturers provide a connector on the instrument so that the frequency may be easily monitored.

11-4. Atmospheric Corrections

a. Refractive index. The accuracy of measurements made with DME depends not only upon the instrument itself but also upon a knowledge of the velocity of light along the measuring path. Techniques to be discussed later reduce this dependence to a minimum in the case of measuring movements in large structures, but in order to make absolute measurements, it is vital to have an accurate knowledge of the refractive index of the air along the line being measured. The refractive index is simply a measure of how much light is slowed down in traveling through a medium other than a vacuum. Some representative refractive indices used with modern DME are given in the following table.

Wavelengths (micrometers)	Source	Refractive Index
0.48	Xenon arc	1.0003101
0.63	HeNe laser	1.0003002
0.84	GaAs laser	1.0002947
0.91	GaAs diode (infrared)	1.0002936

These refractive indices are at standard conditions (temperature °C, pressure 760 mm of mercury, Hg). For any other conditions of temperature and pressure, a new refractive index may be found from

$$n_a = 1+[(n_g-1)/(1+T/273.2)]*(P/760)$$

where

T = temperature, °C

P = pressure, mm of Hg

Generally the atmospheric corrections are supplied in the form of a handy circular slide rule, tables, or a simple nomogram, which gives a parts-per-million correction depending on temperature and pressure. This correction may be either dialed into the instrument or applied directly to the measured distance. The procedure in most cases would be to measure both temperature and pressure at each end of the line. The temperatures and pressures must then be meaned, and parts-per-million correction must be determined from the appropriate source. Then, this correction must be dialed into the instrument before a measurement can be made. In the case of work on dams, this procedure could prove to be awkward. In most cases, it would be simpler to set the parts-per-million dial to zero and keep a record of temperature and pressure to be applied later as a correction.

b. Measurement of temperature and pressure. When absolute accuracy in measuring is required, such as when a baseline is laid out, temperature and pressure measurements play a vital part. The magnitude of the errors possible from the incorrect application of temperature and pressure corrections are: a change of 1 °C or a change of 2.5 mm (0.1 inch) of Hg will cause a 1 ppm change in the observed distance.

(1) Pressure measurements should be made at both ends of the line, and the mean of the two values used in the refractive index equation. If it is not possible to place barometers at both ends of the line, place the barometer at the instrument end, and use the elevations of the two ends together with the pressure measured at the instrument to calculate the pressure at the other end.

(2) Temperature is much more difficult to measure properly. The measuring equipment must be well shielded from the sun's radiation. This can be accomplished by enclosing the thermometer in a reflective insulating shield. However, this permits the heat to build up within the shield, and thus a small fan or some other means must be used to move air over the temperature sensing device so that the true air temperature is read. Also, temperatures measured at the end points of a line near the ground are a poor indication of the true temperature along the line. Studies have shown that during the day, temperatures near the ground are much warmer than those 30 m above the ground. A 5 ºC difference is not uncommon. At night the reverse is true; temperatures near the ground are cooler than those above. Unfortunately, many lines to be measured in deformation surveys are more than 30 m above the ground over most of their lengths. Thus, temperature measurements are one of the major sources of error in the accurate determination of distance.

(3) In measuring dams or other large structures, refractive index errors are less important because displacement values are needed; therefore relative rather than absolute distances may be used.

11-5. Ratios

Index errors (temperature and pressure measuring errors) have been shown to limit the accuracy of DME. However, even when temperature and pressure are measured properly, errors still occur because it is difficult or impossible to measure other than at the end points of the line. Further, refractive index measurements are both time consuming and expensive. This section discusses techniques for reducing refractive index errors in measurements of large structures by using ratios, or reference lines. There are two important rules when using DME:

Rule 1: Refractive index errors, resulting from end point measurements of temperature and pressure, tend to be the same for all lines measured from one point within a short period of time.

Rule 2: The ratios of observed distances, measured from one point within a short period of time, are constant.

Note: For both rules, a short period of time is 30 minutes or less.

a. In Figure 11-3, lines AB and AC are measured from a common point. Rule 1 states that if refractive index measurements are made at points A, B, and C within a short period, the errors in the measurements tend to be the same at all three points. If the true temperature along line AB is 20 °C, but the mean of measurements made at A and B is 24 °C (a condition typical of daytime), then the mean of temperature measurements at the end points of line AC would also be expected to be 4 °C higher than the true temperature along that line. Because 1 °C is approximately equivalent to 1 ppm of distance, both lengths will be in error by 4 ppm. However, if the measured length of AB is divided by the measured length of AC, the resulting ratio will equal the ratio of the true lengths. Thus, the *ratio* of two measured lengths will be more accurate than either of the lengths that were used to form the ratio. For example, AB was measured to be 2,839.611 m, and AC was measured to be 2,241.487 m. Their ratio is AB/AC = 1.26684250. Both lines were in error by 4 ppm because of temperature-measuring errors; therefore, the true lengths were AB = 2,839.611 + 0.0114 (4 ppm) and AC = 2,241.487 + 0.0090 (4 ppm). The ratio of the true lengths is 2,839.6224/2,241.4960 = 1.26684250, the same as the ratio of measured lengths.

b. When ratios are formed from measurements that have had refractive index corrections applied, they will be called *corrected ratios*. The property of the corrected ratio is that it is very accurate. From corrected ratios, angles may be computed that are frequently within a few tenths of an arc second of their true values.

c. A second set of ratios can be obtained from the same measurements by using the data before the

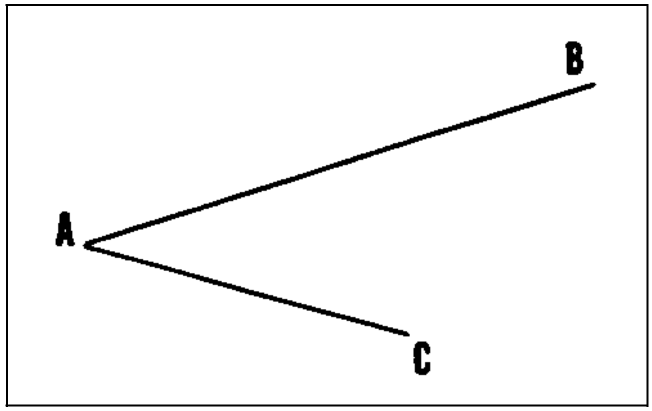

Figure 11-3. Ratio of two lines

application of the refractive index corrections. These are called *observed ratios*, and they have been formed from lines that have had no temperature or pressure corrections applied. Rule 2 states that the observed ratio is constant. This means that the observed ratio of two lines measured today will agree with the observed ratio of the same two lines measured months or years later. This will be true even though the observed lengths of the individual lines have changed greatly because of changes in atmospheric conditions between the two sets of measurements. The observed ratios will not, however, be the same as the corrected ratios unless certain conditions are met. To understand this, let us assume for a moment that an instrument has been set upon a hilltop. In the valley below, two points have been selected that are equidistant from the hilltop stations and are at the same elevation. The observed distances to the two points would appear the same because the distances are equal and both lines pass through roughly the same atmosphere. A point is then selected that is the same distance from the hilltop station as the other points, but with a higher elevation. When the observed distances are recorded, the two lengths to the valley points are the same, but the observed length to the higher elevation point is shorter. Because air density decreases with elevation, the light traversing the higher line travels faster and returns sooner. The instrument then shows the distance to be shorter. Two lessons can be learned from this. The first lesson is that if the mean elevations of two lines measured from a point are the same, the ratio of the observed distances is equal to the ratio of the corrected distances. In the example above, the observed distances to the valley points are the same, and the ratio of the two observed lengths is 1. The true lengths to the two points are the same so that the ratio of the corrected lengths is also 1. This is often the case with dams where the alignment markers along the crest of the dam are all within a few meters of the same elevation. This property of *observed ratios* will be used later on.

d. The second lesson is that when the elevations of the end points to which measurements are being made are different, the ratio of observed lengths is not the same as the ratio of corrected (true) lengths because the refractive indices along the two lines are different. Even though it is not accurate, the observed ratio does not change with time and it may be used to detect changes in position. Furthermore, the observed ratio may be corrected by means of an atmospheric model.

e. In many respects, ratios have properties similar to those of angles. In triangulation, the sum of the three angles of a triangle must equal 180, and a knowledge of two angles permits calculation of the third. Similarly, the product of three ratios obtained from a triangle must equal 1, and a knowledge of two ratios permits calculation of the third. In Figure 11-4, the triangle shown has sides A, B, and C as measured from vertices 1, 2, and 3. The ratio measured from vertex 1 is A_1/B_1, using a counter-clockwise convention (A_1/B_1 rather than B_1/A_1) with the subscript designating the vertex from which the ratio was measured. Two other ratios, B_2/C_2 and C_3/A_3, may also be measured. If the measurements are perfect, $A_1 = A_3$, $B_1 = B_2$, $C_2 = C_3$, and $A_1/B_1 * B_2/C_2 * C_3/A_3 = 1$. If the measurements are not perfect (the usual case), the degree to which the product failed to equal 1 is a measure of the precision of the measurements. If only two ratios were measured, the third may be calculated. For example, $A_1/B_1 = C_2/B_2 * A_3/C_3$. Angles may be calculated directly from the ratios by using a modified cosine formula.

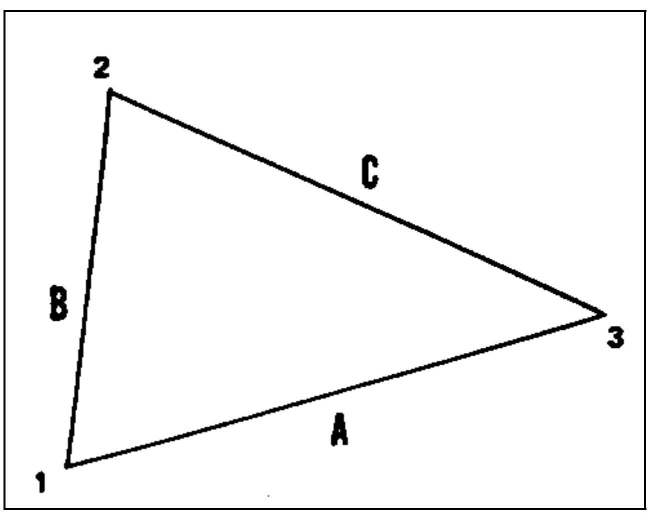

Figure 11-4. Ratios in a triangle

f. The use of ratios yields angles as a result, and the angles determined from the ratios are more accurate than those determined from the lengths alone because a ratio is more accurate than either of the lengths from which it is derived.

g. When the angles of a triangle do not sum to 180, the triangle may be adjusted by taking one-third of the difference between 180 and the sum of the angles and by applying it as a correction to each angle. With ratios, a correction may be made to each ratio.

11-6. 2-D Deformation Monitoring

Sometimes it is not practical to do First- or Second-Order 3-D deformation monitoring. Measurements of movements in large structures can be made very accurately, in two dimensions, by using trilateration techniques. The work consists of two phases, the control network and the structure itself.

a. The control network. In monitoring possible movements of structures, points on the structure must be related to points that have been selected for stability, usually at some distance from the structure itself. These will be called control points, and all movements of the structure will be related to one or more of them. It is important that the control points not move, and for this reason, they should be placed in geological stable positions. They should also afford a good geometry for trilateration measurements. Good geometry, in turn, consists of measuring along the line where movement is expected. For example, if measurements of upstream or downstream movements are required, the control point should be located either upstream or downstream. Further, the point should be at a sufficient distance from the structure so that the end points, as well as the center, can be monitored with good geometry. In Figure 11-5, a dam is shown with both an upstream and a downstream control monument. Geometrically, measurements from the upstream side of the dam will be poor, while those from the downstream side will be much stronger. If movement in two dimensions is desired, a point off the end of the dam should also be chosen (see Figure 11-5). For best results, the angle of intersection (θ) should be 90 degrees. Two selections of control figures are shown in Figure 11-6.

(1) A final criterion for the selection of control monuments is intervisibility. Because the control figure also provides a means of correcting for refractive index, the points selected for control at the ends of the dam must be visible from the upstream and/or downstream points.

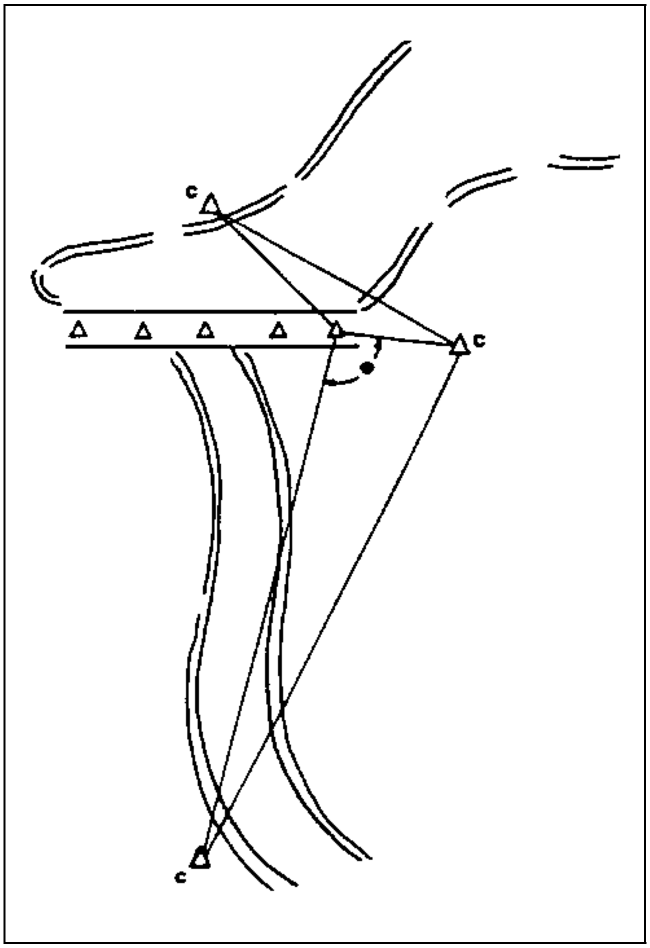

Figure 11-5. Control monuments (c) for a dam

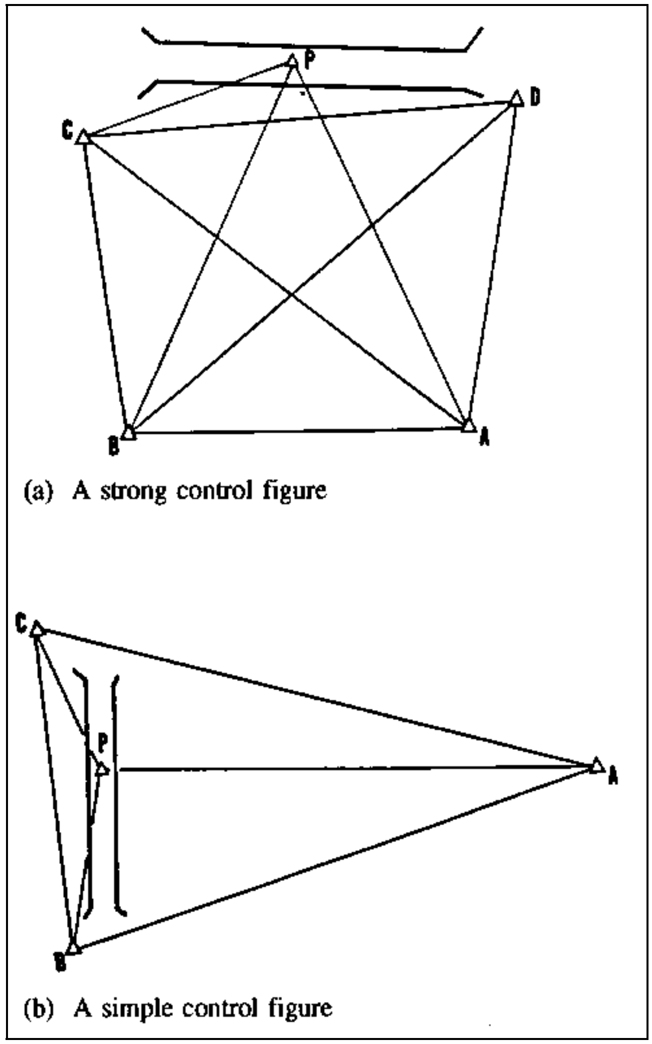

Figure 11-6. Strong and simple control figures

(2) In trilateration, lengths to an unknown station from each of two control points will give the position of the unknown station in two dimensions. Measurements from three control stations will give three positions of the unknown station, and may be used as a check of survey accuracy. Figure 11-6a shows a good control figure for the measurement of a dam. In the control figure, A, B, C, and D are control monuments. All are intervisible. Point P is an unknown station on the dam and is measured from control points A, B, and C. Positions of P are calculated from measurements of lines AP and BP, from lines BP and CP, and from lines AP and CP. The agreement between the three positions obtained for point P is a measure of the accuracy of the survey.

(3) When measurements are made of lines exceeding 600 m, a major source of error is the inability to determine accurately the refractive index along the line. An error in temperature of 1 °C or in pressure of 2.5 mm (0.1 inch) of H_g will cause an error in length of 1 ppm. These errors may be minimized by considering the ratio of two lines that have been measured within 30 minutes of each other. The errors of each line tend to be the same so that taking a ratio greatly reduces the magnitude of the error. This may be shown by again referring to Figure 11-6a. Point P has been selected as a reference point. Its position was chosen so that it would be in stable ground, it would be visible from the other control points, and the lines to it from the other control points would pass through atmospheric conditions similar to those from the control points to unknown positions on the dam.

(4) The first time a dam is visited to make trilateration measurements, both ratios and conventional measurements are made to determine the shape and size of the

control figure. The simplest example would be the triangular figure shown in Figure 11-6b. All control monuments should be occupied by the DME. At each point, measurements should be made to all of the other control monuments within a short period of time. In the case of the triangle ABC in Figure 11-6b, monument A would be occupied and lengths AC and AB measured. Careful refractive index readings should also be taken at both ends of each line as it is measured. Similar measurements should then be made as the DME occupies stations B and C. Each line should then be reduced to the level of spheroid and have the refractive index corrections applied. A typical set of measurements for triangle ABC is:

	Length (in m)	Ratio
A to	C 2,547.447	AC/AB 0.9181349
	B 2,774.589	
B to	A 2,774.583	BA/BC 3.7776155
	C 734.480	
C to	B 734.478	CB/CA 0.2883212
	A 2,547.430	

(AC/AB)*(BA/BC)*(CB/CA) = 1.0000018

<u>Adjusted Angles</u>

A	15°	05'	47.84"
B	64°	35'	55.08"
C	100°	18'	17.08"

By way of comparison, angles calculated from the mean lengths would be:

A	15°	05'	47.59"
B	64°	35'	53.76"
C	100°	18'	18.65"

Note: lengths are spheroid distances in meters.

The adjusted angles determined from corrected ratios are more accurate than the angles determined from the means of the lengths of the sides because ratios are more accurate than the lengths of which they are composed.

(5) It may be seen from the above example that the result of working with ratios is angles, and that in effect very accurate triangulation is being carried out using DME. As in the case of triangulation, a base line is necessary to determine the scale when ratios are used. Choose one of the sides of the triangle to serve as a baseline, and use the mean length as the scale for the triangle. In this example, AB has been chosen and its length is 2,774.586 m. Next, by using the sine formula and the angles determined from ratios, the other two sides may be determined:

2,774.586/sin C = BC/sin A = AC/sin B

BC = 734.481 AC = 2,547.443

(6) The angles obtained by these methods are of the highest accuracy. The scale, however, is only as accurate as the mean of the two measurements of the baseline. Fortunately, this is not a serious problem with measurements of dams because changes in lengths are desired rather than the absolute lengths themselves.

(7) The final task in establishing the control network is to assign coordinates to A, B, and C. These may be fitted into an existing network, or a local control net may be set up for the project.

(8) At a later date, the control figure may once again be occupied. The same procedure may be used, and the angles determined and compared with those obtained during the first survey. This, however, requires the use of temperature and pressure measuring devices each time the figure is surveyed.

(9) NOTE: An easier method is to use the observed ratios, for these do not require knowledge of the refractive index. Remember that the observed ratios remain constant, and thus comparison of observed ratios from the first survey with observed ratios from the second survey is sufficient to determine whether any of the control monuments have moved. In fact, measurements of temperature and pressure need only be made of the control lines in order to give the proper scale to the figure. And these measurements need only be made the first time a project is surveyed. From that time on, only observed distances are required. In addition, all of the measurements from the control monuments to stations on the dam will be observed distances. Measurements of temperature and pressure are not necessary.

b. Points on the dam. When positions have been established for the monuments in the control figure, observed ratios will be used to determine the refractive index corrections for measurements of points on the dam. Referring again to Figure 11-6b, the lines AC, AB, and BC have been corrected for refractive index and may be used as reference lines. For measurements from control monument A, either AC or AB may be used as a reference line. A good reference line is one which traverses approximately the same atmosphere as is found along the lines to points on the dam and is almost the same length or longer. If we call the corrected length of the reference line R_{corr} and the observed length of the same line R_{obs}, the following equation may be written

$$R_{obs} \times k = R_{corr}$$

Where k is a constant owing to the atmospheric conditions along the line at the time it was measured. Because the reference line has been selected to travel through approximately the same atmosphere as that to points on the dam, we may say that k is also the atmospheric constant for lines measured to the dam. If P_{obs} is the observed length to a point on the dam, then the corrected distant, P_{corr}, may be found from

$$P_{obs} \times k = P_{corr}$$

This technique enables the surveyor to correct for refractive index without using temperature and pressure measuring equipment. However, k is not really a constant. It changes slowly with time. For this reason, it must be remeasured at approximately 30-minute intervals, and it must be assumed it changes in a linear fashion.

(1) The following example will detail the previous phenomena. In Figure 11-7, the DME has been set up at A. Measurements are made of AC, AP_1, AP_2, AP_3, and again AC.

After the observed lengths have been reduced to the level or the spheroid, the measurements from control monument A were recorded as listed in Table 11-1.

The first and last measurements are of AC. The length of AC is known and is used as a reference line to calculate the value of the refractive index constant. At first, the constant was 1.0000459 (2,547.443/2,547.326), but because of changes in the atmosphere, it changed to 1.0000440 (2,547.443/2,547.331). The value of k at intermediate times may be found by assuming that the change was linear. Thus, a value of k may be found for the times when P_1, P_2, and P_3 were measured. Applying the appropriate value of k to the observed length, D_{obs}, of AP_1 gives 2,477.075 * 1.0000454 = 2,477.187 as its corrected length, D_{corr}.

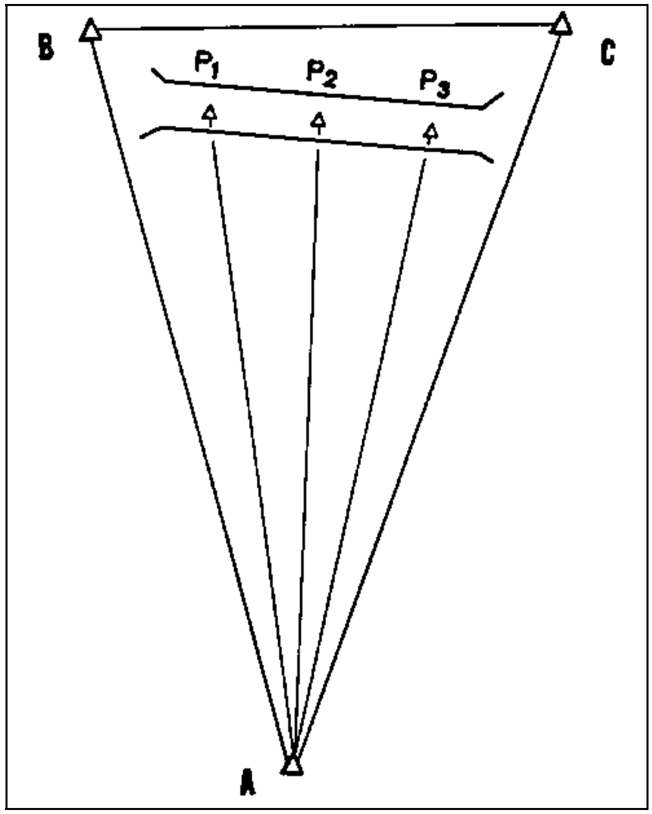

Figure 11-7. Use of a reference line

Table 11-1
Measurement Taken (Example Deformation Survey)

To Station	Time	Observed Length (D_{obs})	Refractive Index Constant (k)	Corrected Distance (D_{corr})
C	1330	2,547.326	1.0000459	2,547.443*
P_1	1335	2,477.075	1.0000454	2,477.187
P_2	1340	2,407.354	1.0000449	2,407.462
P_3	1345	2,445.152	1.0000445	2,445.261
C	1350	2,547.331	1.0000440	2,547.443*

*Note: AC is the reference line

(2) Any length in a control figure may serve as a reference line, although some lines will be better than others. From A, AB would also serve. From B however, BC would be a better choice than BA because it passes through an atmosphere similar to that found in measuring from B to P_1, P_2, and P_3.

c. Reduction to the spheroid. Mention has been made of reducing lines either to the level or the spheroid. In very accurate work where lines exceed 1 km, the surface upon which a survey is being made can no longer be considered a plane. If distances are reduced to the level and used to calculate angles, the angles thus obtained may not agree with angles obtained from a theodolite. Further, the position of a point calculated from the lengths to two control monuments may not agree with the position of the same point when measured from two other control monuments. To prevent problems of this type, figures with line lengths in excess of 1 km should be reduced to the spheroid instead of the level. The equation to be used is

$$D_s = R \sqrt{\frac{[D_1 - (e_2 - e_1)]\ [D_1 + (e_2 - e_1)]}{(R + e_2)\ (R + e_1)}}$$

where

D_s = Spheriod chord distance

R = Earth radius (6,372,000 meters)

D_1 = Observed distance from the DME

e_1 = Elevation + H.I. of the instrument

e_2 = Elevation + H.I. of the reflector

d. RLR deformation survey example. The example survey developed in the following paragraphs combines the principles developed for RLR method of deformation monitoring. This section will combine these elements to show how they may be used for a precise survey of a dam.

(1) A diagram of the control setup and dam are shown in Figure 11-8. Control pedestals have been set at points C1, C2, C3, and C4. Markers A1 through A6 have been set along the crest of the dam, and T1 and T2 have been set near the toe of the dam. Elevations have been measured to obtain the list in Table 11-2.

(2) Each of the control monuments were occupied with an EDM, and measurements were made to the other three control monuments. Temperatures and pressures were also taken at both ends of the lines. After measuring the control lines, the lengths to stations on the dam were measured from three of the control monuments. Temperatures and pressures were not taken for these lines.

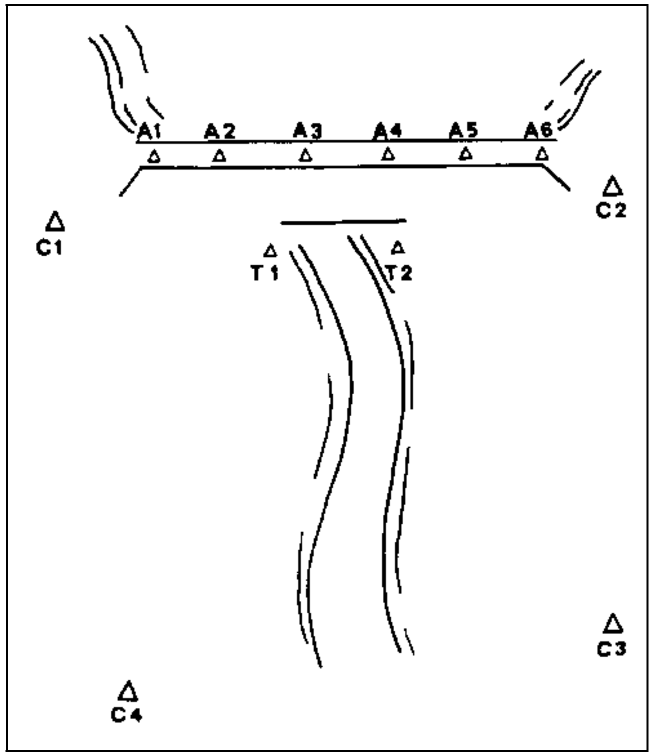

Figure 11-8. Fictitious dam

Table 11-2
Elevations for Example Deformation Survey

Point	Elevation (m above sea level)
A1	410.724
A2	410.718
A3	410.706
A4	410.721
A5	410.712
A6	411.245
C1	419.911
C2	413.275
C3	463.701
C4	521.537
T1	329.623
T2	329.394

(3) On a separate occasion, the following lengths were measured from C3 (Table 11-3).

Measurements began with the control figure. Either C1 or C2 could have been used for a reference line, but in this case C1 has been chosen. Because it was the reference line, it was measured before and after the remaining control lines. This practice helped to check for both drift

Table 11-3
Measurements from C3 for Example Deformation Survey

#	To	Time	Observed Distance D_S (meters)	Mean Temp. (°C)	Mean Press. (inches Hg)
1	C1	0930	1,081.105	16.4	28.26
2	C4	0935	945.032	16.4	28.09
3	C2	0940	703.788	17.0	28.27
4	C1	0945	1,081.104	16.7	28.26
5	C1	1025	1,081.101		
6	A1	1035	968.241		
7	A2	1045	924.456		
8	C1	1050	1,081.103		
9	A3	1100	882.721		
10	A4	1115	843.323		
11	C1	1120	1,081.104		
12	A5	1130	806.626		
13	A6	1145	772.950		
14	C1	1150	1,081.104		
15	C1	1300	1,081.100		
16	T1	1305	872.886		
17	T2	1315	836.021		
18	C1	1300	1,081.097		

in the instrument and in the atmospheric conditions. When the control lines were completed, the operator next measured to points on the dam. Forty minutes had elapsed after completion of the contour line measurements before the field party with reflectors were set up on the dam. Because the reference line should be measured approximately every 30 minutes, the observed distance to C1 was again measured (measurement 5). A reflector was left unattended at C1 because it was no longer necessary to read the temperature and pressure. Remember temperature and pressure measurements are made only on the control lines and only when a study is made for the first time at a particular dam. The next time the dam is visited, perhaps 6 or 12 months later, it will not be necessary to measure refractive index. Possible movement in the control figure may be checked at that time by a comparison of ratios of observed distances.

(4) Measurements were made that same afternoon from C1. Only the control lines were measured. Three sets of positions will be obtained for the stations on the dam from C2, C3, and C4. Measurements from C1 would do little to improve the accuracy of these positions in the upstream-direction. Table 11-4 gives the lengths from C1 recorded for that session.

(5) A week later, monument C4 was occupied and measurements were taken. These measurements are shown in Table 11-5.

Table 11-4
Measurements from C1 for Example Deformation Survey

#	To	Time	Observed Distance D_S (meters)	Mean Temp. (°C)	Mean Press. (inches Hg)
19	C2	1400	566.212	19.0	28.28
20	C3	1405	1,081.095	18.8	28.20
21	C4	1410	989.418	18.5	28.09
22	C2	1415	566.215	18.8	28.28

Table 11-5
Measurements from C4 for Example Deformation Survey

#	To	Time	Observed Distance D_S (meters)	Mean Temp. (°C)	Mean Press. (inches Hg)
23	C1	0835	989.446	6.1	28.85
24	C2	0840	1,138.277	6.1	28.87
25	C3	0845	945.050	5.8	28.78
26	C1	0850	989.445	6.2	28.85
27	C1	0900	989.444		
28	A1	0905	1,031.587		
29	A2	0915	1,042.973		
30	A3	0925	1,057.756		
31	C1	0930	989.438		
32	A4	0940	1,075.788		
33	A5	0945	1,096.925		
34	A6	0955	1,120.924		
35	C1	1000	989.432		
36	T1	1010	981.303		
37	T2	1020	987.682		
38	C1	1025	989.431		

(6) Later that day, monument C2 was occupied and measurements were taken. These measurements are shown in Table 11-6 and completed the field measurement phase.

Table 11-6
Measurements from C2 for Example Deformation Survey

#	To	Time	Observed Distance D_S (meters)	Mean Temp. (°C)	Mean Press. (inches Hg)
39	C1	1230	566.225	8.1	29.04
40	C4	1235	1,138.273	7.6	28.87
41	C3	1240	703.799	7.8	28.97
42	C1	1245	566.225	8.3	29.04
43	A1	1250	398.146		
44	A2	1300	337.350		
45	A3	1310	276.652		
46	C1	1315	566.225		
47	A4	1320	216.070		
48	A5	1330	155.828		
49	A6	1335	96.436		
50	C1	1345	566.224		

(7) The first step in the data reduction is to reduce all the lines (D_S) to the spheroid. This has been done and is shown in Table 11-7.

Table 11-7
Corrected Line Lengths

#	C3 To	Time	Observed Distance D_{obs} (meters)	Corrected Distance (meters)
1	C1	0930	1,080.143	1,080.156*
2	C4	0935	943.188	943.201*
3	C2	0940	701.931	701.940*
4	C1	0945	1,080.142	1,080.155*
5	C1	1025	1,080.141	(1,080.155)
6	A1	1035	966.724	966.736
7	A2	1045	922.873	922.884
8	C1	1050	1,080.141	(1,080.154)
9	A3	1100	881.068	881.078
10	A4	1115	841.599	841.609
11	C1	1120	1,080.142	(1,080.154)
12	A5	1130	804.828	804.837
13	A6	1145	771.115	771.124
14	C1	1150	1,080.142	(1,080.154)
15	C1	1300	1,080.138	(1,080.154)
16	T1	1305	862.473	862.486
17	T2	1315	825.111	825.125
18	C1	1320	1,080.135	(1,080.154)
#	**C1 To**	**Time**	**Observed Distance D_{obs} (meters)**	**Corrected Distance (meters)**
19	C2	1400	566.136	566.144*
20	C3	1405	1,080.133	1,080.149*
21	C4	1410	984.112	984.128*
22	C2	1415	566.139	566.147*
#	**C4 To**	**Time**	**Observed Distance D_{obs} (meters)**	**Corrected Distance (meters)**
23	C1	0835	984.140	984.137*
24	C2	0840	1,133.034	1,133.030*
25	C3	0845	943.206	943.203*
26	C1	0850	984.139	984.136*
27	C1	0900	984.138	(984.134)
28	A1	0905	1,025.543	1,025.540
29	A2	0915	1,036.993	1,036.992
30	A3	0925	1,051.857	1,051.858
31	C1	0930	984.132	(984.134)
32	A4	0940	1,069.987	1,069.991
33	A5	0945	1,091.232	1,091.238
34	A6	0955	1,115.403	1,114.411
35	C1	1000	984.126	(984.134)
36	T1	1010	962.289	962.297
37	T2	1020	968.747	968.756
38	C1	1025	984.125	(984.134)
#	**C2 To**	**Time**	**Observed Distance D_{obs} (meters)**	**Corrected Distance (meters)**
39	C1	1230	566.149	566.147*
40	C4	1235	1,133.149	1,133.027*
41	C3	1240	701.942	701.940*
42	C1	1245	566.149	(566.146)
43	A1	1250	398.112	398.110
44	A2	1300	337.318	337.316
45	A3	1310	276.622	276.621
46	C1	1315	566.149	(566.146)
47	A4	1320	216.041	216.040
48	A5	1330	155.797	155.796
49	A6	1335	96.408	96.408
50	C1	1345	566.148	(566.146)

(Continued)

Note: * - Denotes length corrected from temperature and pressure measurements. ( ) - Denotes true length.

(8) When the lines have been reduced to the spheroid, the next step is to define the size and shape of the control figure, in this case a doubly braced quadrilateral. There are several ways to do this. One way is, since the figure contains four triangles, these may be individually treated in the same manner as the triangle in Figure 11-6a.

Another way would be to use the means of the six lines in the figure and adjust these by means of a quadrilateral adjustment. This is the technique that was used in the present case to obtain the following adjusted lengths:

C1 to C2	566.146 meters
C1 to C3	1,080.154
C1 to C4	984.134
C2 to C3	701.940
C2 to C4	1,133.029
C3 to C4	943.202

(9) The control figure may be fit into an existing coordinate system or a local system may be devised just for the dam. For the fictitious dam, a local system was used. C4 was selected as a starting point and was assigned coordinates of x = 1,000.000 and y = 1,000.000. The coordinates of C3 were then chosen to place C3 at a distance of 943.202 m from C4; they are x = 1,943.202 and y = 1,000.000; The placement of C4 and C3 has determined the scale and orientation of the figure. Using the positions of C3 and C4 and the appropriate lengths, the positions of C1 and C2 can be determined to be:

C1: x = 1,366.527
y = 1,913.333

C2: x = 1890.936
y = 1699.991

(10) **NOTE: The establishment of the control figure needs be done only once. From that time on, it is only necessary to check for movements of the control monuments. This may be done by comparing observed ratios taken at some later time with the original set.**

(11) Returning to Table 11-7, one may now calculate the corrected lengths D_{corr} to the stations on the top and toe of the dam from the control monuments. This is done by using reference lines to make refractive index corrections.

(12) Measurements 15 through 18 from Table 11-7 are given in Table 11-8.

Table 11-8
Changes of Correction Factor with Time

#	C3 To	Time	D_{obs} (meters)	Correction Factor	D_{corr}* (meters)
15	C1	1300	1,080.138	1.0000148	(1,080.154)
16	T1	1305	862.473	1.0000155	862.486
17	T2	1315	825.111	1.0000169	825.125
18	C2	1320	1,080.135	1.0000135	(1,080.154)

* () denotes true length.

(13) At 1300, when the distance to C1 was measured, the observed distance, D_{obs}, was found to be 1,080.138 m. This line, C3 to C1, is a part of the control figure, and its correct length has been determined to be 1,080.154 m. The atmospheric correction at 1300 may then be found by dividing. The correction is 1,080.154/ 1,080.138 = 1.0000148. Later, at 1320, the atmospheric correction has become 1.0000176. Assuming the change in correction has been linear as a function of time over the 20-minute interval, we may calculate the correction factor at 1305 and 1315 when observed distances were measured to T1 and T2. Multiplying the observed distance by the corresponding atmospheric correction gives the corrected distance, D_C, to T1 and T2. Thus in Table 11-7, the values in parenthesis in column 5 are the correct or true lengths of reference lines, and the values without an asterisk or parenthesis are the corrected lengths that have been calculated from reference lines.

(14) Finally, with the corrected lengths and the coordinates of the control monuments from which they were measured, it is possible to calculate the positions of the points on the dam. Because three lengths were measured to stations on the crest of the dam, three solutions will be obtained. Geometrically, some solutions will be superior to others. For stations at the toe of the dam, only one solution is possible.

(15) In Table 11-9, positions of the crest and toe markers are given for various line combinations, In the case of the crest markers, an adjusted position is also given.

(16) If desired, alignment may be determined from positions. Using the crest stations A1 and A6 as end points, the alignment of A2 through A5 is given in Table 11-10. T1 and T2 are also included in the alignment to help monitor any tilt in the dam. Alignment done from positions is not affected by curved dams, by bends, or by differences in elevations.

Table 11-9
Crest and Toe Station Positions

Station	X	Y	From
A1	1,533.713	1,875.726	C2 to C3
	1,533.710	1,875.720	C2 to C4
	1,533.705	1,875.723	C3 to C4
	1,533.709	1,875.722	Adjusted
A2	1,590.161	1,852.688	C2 to C3
	1,590.158	1,852.682	C2 to C4
	1,590.153	1,852.685	C3 to C4
	1,590.157	1,852.684	Adjusted
A3	1,646.583	1,829.648	C2 to C3
	1,646.588	1,829.656	C2 to C4
	1,646.594	1,829.652	C3 to C4
	1,646.589	1,829.653	Adjusted
A4	1,703.041	1,806.615	C2 to C3
	1,703.038	1,806.609	C2 to C4
	1,703.033	1,806.613	C3 to C4
	1,703.037	1,806.612	Adjusted
A5	1,759.465	1,783.585	C2 to C3
	1,759.467	1,783.588	C2 to C4
	1,759.470	1,783.584	C3 to C4
	1,759.468	1,783.586	Adjusted
A6	1,815.919	1,760.547	C2 to C3
	1,815.915	1,760.542	C2 to C4
	1,815.912	1,760.545	C3 to C4
	1,815.915	1,760.544	Adjusted
T1	1,568.152	1,776.672	C3 to C4
T2	1,608.187	1,754.053	C3 to C4

Table 11-10
Alignment

Station	Distance from A1 (meters)	Distance off Line (meters)*
A2	60.968	0.00
A3	121.919	- 0.001
A4	182.888	+ 0.001
A5	243.836	- 0.004
T1		+78.691
T2		+84.505

* + = Downstream.
  - = Upstream.